ITERATIVE DETERMINATION OF THE AEROSOL EXTINCTION COEFFICIENT PROFILE AND THE MEAN EXTINCTION-TO-BACKSCATTER RATIO FROM MULTIANGLE LIDAR DATA

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ABSTRACT

A method to determine the aerosol extinction coefficient profile and the mean extinction-to-backscatter ratio from scanning lidar data has been developed. The only *a priori* information required is the molecular extinction coefficient profile. In this initial study we consider the simplest case where the extinction-to-backscattering ratio is constant with height. The extinction-to-backscatter ratio is determined iteratively by comparing the retrieved particulate extinction coefficient profiles obtained with two independent multiangle inversion methods from the same set of lidar data. The iterative method has been tested with synthetic data and was successfully applied to experimental data.

1. INTRODUCTION

Due to the indeterminacy of the lidar equation inversion algorithms have to resort to certain assumptions in order to determine atmospheric backscatter and extinction. One approach to the inversion problem involves two- or multiangle methods. Most of these methods either assume a unique relationship between optical depth and elevation angle and/or are based on the assumption that scattering within horizontal layers is homogeneous [1-6]. Reference or *a priori* data may also be included as a constraint [7]. In order to reduce the uncertainty introduced by these assumptions, we investigate the possibility of combining the two-angle minimization approach (TAMI) [6] with Hamilton's [5] method. The key point is that these methods, when applied to the same scanning lidar data, are complementary. Using Hamilton's method, the mean particulate extinction coefficient can be determined without an *a priori* selected value of the particulate extinction-to-backscatter ratio (lidar ratio), whereas in TAMI, the lidar ratio is a prerequisite. However, unlike TAMI, Hamilton's method does not allow one to retrieve accurate local extinction coefficient profiles. We will show that combining those methods provides a means to simultaneously determine the vertical profile of the particulate extinction coefficient and the mean lidar ratio.

2. METHOD

The method combines TAMI with the multiangle method put forth by Hamilton in an iterative manner. In the first step, the total optical depth $\tau(0,h)$ to height h is determined by linear regression from lidar measurements $P_i(h)$ at different elevation angles φ_i (i=1…N) using Hamilton's method, which basic equation can be written as

$$\ln\left[P_i(h)(h/\sin\varphi_i)^2\right] = \ln\left[K\beta(h)\right] - 2\,\tau(0,h)/\sin\varphi_i, \qquad (1)$$

where $\beta(h)$ is the total (molecular and particulate) backscatter coefficient and K is a lidar system constant. After the molecular constituent has been removed from the total optical depth, the mean particulate extinction coefficient profile for heights above the zone of incomplete overlap h_1 is computed as $\langle\alpha_p(h_1,h)\rangle = [\tau_p(0,h)-\tau_p(0,h_1)]/(h-h_1)$. In a second step the local particulate extinction coefficient profile is computed from lidar data along the same elevation angles φ_j (j=1, 2) but now using TAMI in the following way:

$$\alpha_{p,j}(h) = \frac{Z_j(h)}{C_j - 2\int_{h_1/\sin\varphi_j}^{h/\sin\varphi_j} Z_j(x)\,dx} - S\frac{3}{8\pi}\alpha_m(h), \qquad (2)$$

with $Z_j(h)=P_j(h)^2 Y_j(h)$, where $Y_j(h)$ is a transformation function [8],

$$Y_j(h) = S\exp\left\{-2\int_{h_1/\sin\varphi_j}^{h/\sin\varphi_j}\left[S\frac{3}{8\pi}-1\right]\alpha_m(x)\,dx\right\}, \qquad (3)$$

where S is the lidar ratio, which is assumed to be constant, and $\alpha_m(h)$ is the molecular extinction coefficient profile. The calibration constants C_j are determined by minimizing the function

$$\eta(h) = \ln\left[\frac{Z_1(h)}{Z_2(h)}\right] - \ln\left(\frac{C_1}{C_2}\right) - \ln\left[1 - \frac{2\int_{h_1/\sin\varphi_j}^{h/\sin\varphi_j} Z_1(x)\,dx}{C_1}\right] + \ln\left[\frac{2\int_{h_1/\sin\varphi_j}^{h/\sin\varphi_j} Z_2(x)\,dx}{C_2}\right]. \qquad (4)$$

Now the mean particulate extinction coefficient profile can be computed from the TAMI local $\alpha_p(h)$ profiles (Eq. 2) according to

$$<\alpha_p(h_1,h)>=\left[\int_{h_1}^{h}\alpha_p(h)dh\right]\Big/(h-h_1). \tag{5}$$

In the next step the solutions for $<\alpha_p(h_1,h)>$ obtained using Hamilton's method and TAMI are compared. The lidar ratio in Eq. (2) is then varied until best agreement is reached. This iterative procedure allows one to determine the mean *S* and the local particulate extinction coefficient profile simultaneously that provide the best agreement between TAMI and Hamilton's method.

3. TEST WITH SYNTHETIC DATA

Synthetic data representing a distinct and mildly turbid atmospheric boundary layer (up to 1000 m) and clear troposphere (1000 m to 3200 m) are used to test the iterative method. A lidar ratio of *S*=50 sr has been used to compute the lidar signal at elevation angles 15° and 30° (Fig. 1).
Applying the procedure described above, we compute the mean $<\alpha_p(h_1,h)>$ profile using Hamilton's method and TAMI profiles using different values for the lidar ratio. The resulting profiles for an initial value *S*=17 sr are shown in Fig. 2 along with the model profile of $<\alpha_p(h_1,h)>$. Note that $<\alpha_p(h_1,h)>$ is determined piecewise in *h* with Hamilton's method, whereas for the calculation of the TAMI and model $<\alpha_p(h_1,h)>$ integrated values are used, and hence the profiles are smoother. The solution obtained with Hamilton's method agrees well with the model profile except for strong fluctuations.

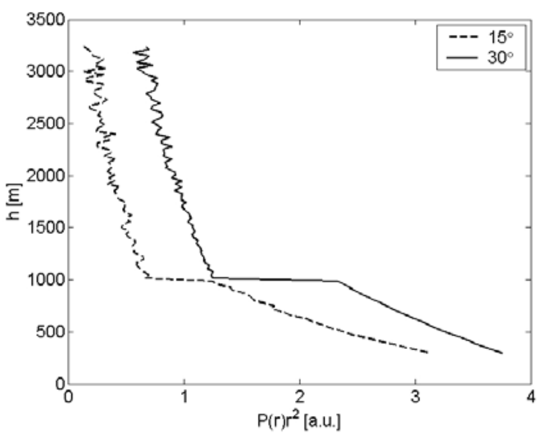

Fig. 1. Synthetic data representing a distinct and mildly turbid boundary layer and clear free troposphere. *S*=50 sr has been used to compute *P*(*r*). The zone of incomplete overlap extends up to *h*=300 m.

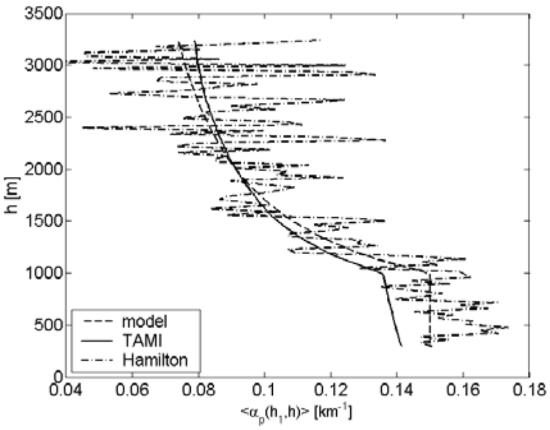

Fig. 2. Comparison of mean extinction coefficient profiles. *S*=17 sr has been used for the inversion with TAMI. The Hamilton profile exhibits strong fluctuations.

However, the TAMI solution with *S*=17 sr deviates systematically from the solution obtained using Hamilton's method especially within the boundary layer. Indeed, the comparison between the retrieved and model mean extinction coefficient profile, also shown in Fig. 2, confirms that using *S*=17 sr will yield shifted inversion results. The overall relative error between the model and TAMI (with *S*=17 sr) $<\alpha_p(h_1,h)>$ is 4.7%. Within the boundary layer (up to 1000 m) the error is 7.7% and in the free troposphere (1000 m to 3200 m) the error is 3.7%.
For the next iteration we choose *S*=90 sr. Again, the mean particulate extinction coefficient profile is computed using Eq. (2) and compared to the Hamilton solution. This is shown in Fig. 3, along with the model profile of $<\alpha_p(h_1,h)>$. This time the TAMI $<\alpha_p(h_1,h)>$ profile differs significantly from the Hamilton and model profile in the boundary layer and also in the lower part of the free troposphere.

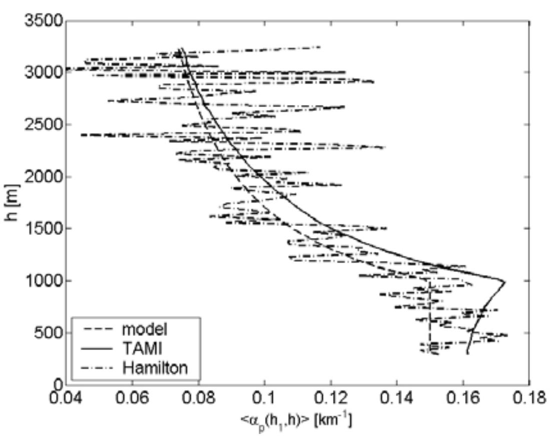

Fig. 3. Comparison of mean extinction coefficient profiles. *S*=90 sr has been used for the inversion with TAMI.

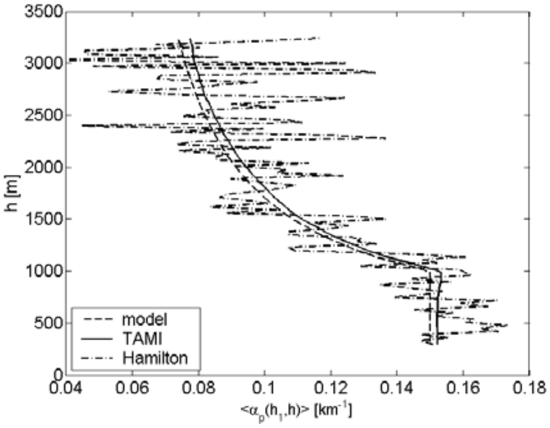

Fig. 4. Comparison of mean extinction coefficient profiles. S=50 sr has been used for the inversion with TAMI.

The relative error in the retrieved mean $<\alpha_p(h_1,h)>$ (model vs TAMI) is 10.3% within the boundary layer, 7.3% in the free troposphere, and 8.1% overall.
For the third iteration, the correct value S=50 sr is used. Fig. 4 shows the comparison between the $<\alpha_p(h_1,h)>$ profiles obtained using Hamilton and TAMI, along with the model profile. The agreement between all the profiles is good. The relative error (model vs TAMI) for the height range 300 m to 1000 m is 1.7%. From 1000 m to 3200 m, the relative error is 3.3%, and the overall relative error is 2.9%.
The results in Figs. 2-4 demonstrate that when the mean extinction coefficient values obtained from the Hamilton method is used to constrain the TAMI retrieval, the result is a low-noise profile close to the true one.

4. APPLICATION TO EXPERIMENTAL DATA

Next we apply the iterative method to data obtained with the Institute for Tropospheric Research

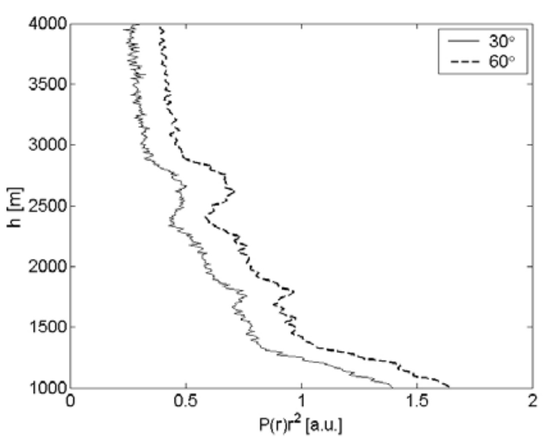

Fig. 5. Lidar data at 532 nm averaged over one hour (04:22 to 05:22 UTC) taken on 25 February 1999 during the INDOEX experiment.

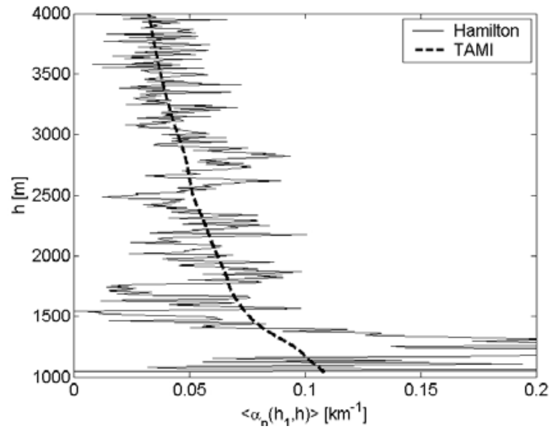

Fig. 6. Mean extinction coefficient $\alpha_p(h_1,h)$ using Hamilton's method and TAMI (S=50 sr).

(ITR, Leipzig, Germany) lidar system during the Indian Ocean Experiment (INDOEX). A description of INDOEX can be found elsewhere [e.g. 9], and the specifications of the ITR lidar are given in [10]. The lidar system was set up to take data for five-minute periods at 30º and 60º elevation angles. A time segment of one hour was chosen for analysis. The time-averaged vertical profiles of the background-subtracted and range-corrected lidar signal $P(r)r^2$ along elevation angles 30º and 60º for the 532 nm wavelength channel used here are shown in Fig. 5. The best agreement between $<\alpha_p(h)>$ from Hamilton and TAMI was obtained for S=50 sr, which is shown in Fig. 6.
The resulting local extinction coefficient profile is shown in Fig. 7 along with the molecular extinction coefficient profile. Notice that the retrieved local $\alpha_p(h_1,h)$ profile resolves both layers at ~1700–1900 m and at ~2400–2900 m.

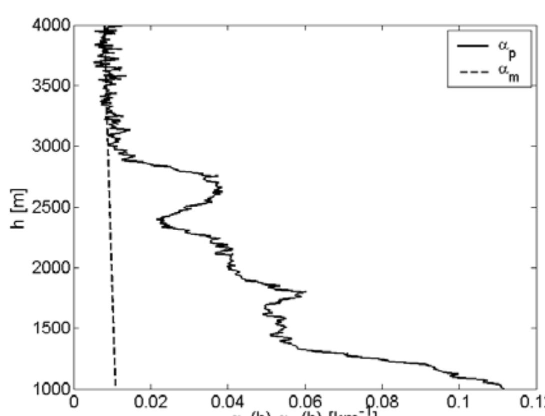

Fig. 7. Local particulate extinction coefficient profile $\alpha_p(h_1,h)$ obtained using TAMI with S=50 sr. Also shown is the molecular extinction coefficient profile $\alpha_m(h)$.

5. SUMMARY

The combination of TAMI with Hamilton's method allows one to determine the local particulate extinction coefficient profile and the mean lidar ratio from scanning lidar data in an iterative manner. The *a priori* information needed is the molecular extinction coefficient profile. The test of the method with synthetic data exhibiting two strongly different atmospheric regimes showed that the $\alpha_p(h_1,h)$ profile can be retrieved with acceptable accuracy. The method also proved to be stable when applied to experimental data. Here the assumption is used that the lidar ratio is constant with height, so that the practical application of the iterative method is limited. Future work will focus on the possibility of using a height-dependent lidar ratio to further improve inversion accuracy.

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